

Gamma Rays from the Tycho Supernova Remnant: Leptonic or Hadronic?

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Recent *Fermi* and *VERITAS* observations of the prototypical Type Ia supernova remnant (SNR) Tycho have discovered γ rays with energies E in the range $0.4 \text{ GeV} \lesssim E \lesssim 10 \text{ TeV}$. Crucial for the theory of Galactic cosmic-ray origin is whether the γ rays from SNRs are produced by accelerated hadrons (protons and ions), or by relativistic electrons. Here we show that the broadband radiation spectrum of Tycho can be explained within the framework of a two-zone leptonic model, which is likely to apply to every SNR. A model with hadrons can also fit the radiation spectrum. The hadronic origin of γ -rays can be confirmed by *Fermi* spectral measurements of Tycho and other SNRs at $\lesssim 300 \text{ MeV}$.

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I. INTRODUCTION

Tycho (G120+1.4, 3C 10) is the bright spherical supernova remnant (SNR) of SN 1572 [1] with a diameter of $\approx 8'$. The distance d to the source is not well-established, but is in the range $d \approx 1.5 - 4 \text{ kpc}$ (e.g., [2]). The narrow $\theta_{\text{rim}} \approx 4''$ spherical rim of hard X-ray emission is coincident with the outer edge of the radio emission [3] and is explained by synchrotron emission of relativistic electrons accelerated to TeV energies [4] by a forward shock moving with speed $v_{\text{sh}} \approx 4600 (d/2.3 \text{ kpc}) \text{ km s}^{-1}$ [5]. Infrared observations from AKARI [6] between 9 and 160μ reveal thermal dust emission in the NE and NW shells. The soft X-rays also reveal a rich line structure implying significant thermal radiation [7].

Gamma-ray fluxes from Tycho between ≈ 1 and 10 TeV have been recently reported by the VERITAS collaboration [8]. The Fermi LAT Collaboration announced a detection in the energy range from ≈ 0.4 to 60 GeV [9], with energy spectral index $\alpha \approx 1.3$. The total Fermi and VERITAS spectra are described by a single power law with $\alpha \approx 1.1 - 1.2$ from $\approx 500 \text{ MeV}$ to 10 TeV . Nonthermal emission at lower frequencies, from radio through X-rays, is universally attributed to synchrotron radiation, which is a signature of primary electron acceleration.

In leptonic models, the γ rays could result from electron bremsstrahlung and/or Compton-scattering processes. In hadronic models the γ rays arise from the decay of, predominantly, π^0 mesons produced in interactions of cosmic-ray protons with gas and dust in the remnant. By modeling its broadband radiation fluxes, Morlino & Caprioli [10] argue that the reported γ -ray fluxes provide strong evidence for hadronic acceleration in Tycho as the leptonic models seem to fail. A similar conclusion was derived by Völk et al. [11] on the basis of the then-existing upper limits of the GeV-TeV γ -rays. Because of the fundamental importance to the theory of SNR origin of Galactic cosmic rays, here we undertake a detailed analysis of the robustness of those claims.

Implicit in the previous modeling is that the detected

synchrotron and Compton emissions are both produced by the very same population of relativistic electrons. This is the working assumption of the commonly used single-zone model approach. In a SNR environment with spatially non-uniform magnetic fields a more realistic description of the nonthermal emission should allow at least two zones [12, 13], where zone 1 represents a strong magnetic-field region in the shock vicinity where acceleration is strong, and zone 2 adjacent (further downstream) to zone 1, with larger volume but lower magnetic field, into which the zone 1 electrons escape by convection with plasma and/or by diffusion. Because the synchrotron emissivity in zone 2 is significantly lower than in zone 1, while the target photon field in both zones is basically the same, the Compton γ -ray fluxes in the two-zone model can greatly exceed the predictions of the single-zone model.

Within this framework, we show that a leptonic model alone can explain well the reported radio through γ -ray data of Tycho. The TeV γ rays are made primarily by Compton emission, and bremsstrahlung produces most of the radiation at GeV energies. The two-zone model is described in Section 2, model parameters and interpretation of the Tycho's broadband spectrum are given in Section 3. As concluded in Section 4, the most important confirmation of the hadronic cosmic ray hypothesis remains the detection of the π^0 -decay feature.

II. TWO-ZONE MODEL FOR SNRS

It is widely believed that cosmic rays are accelerated through Fermi processes by SNR shocks. Both first-order (shock) and second-order (stochastic) processes rely on differences of magnetic field in different regions over which particle diffuse. Strong magnetic fields favored for efficient acceleration can be produced in the vicinity of the strong forward shock through non-linear amplification of the magnetic turbulence/Alfvén waves by the cosmic-ray ions accelerated at the shock (e.g., [14, 15]).

The narrow $\theta_{\text{rim}} \approx 4''$ spherical rim of hard X-ray emission [3] is evidence for such processes operating at the forward shock of Tycho. Interpretation of the rim width $h \approx 1.93 \cdot 10^{-2} d_{\text{kpc}} \text{ pc}$, at the source distance $d_{\text{kpc}} \equiv d/1 \text{ kpc}$, as due to fast synchrotron cooling of $\gtrsim 10 \text{ TeV}$ electrons implies a high magnetic field in the rim, $B \gtrsim 400 \mu\text{G}$ [11]. In effect, this explanation leads to a single-zone model where all the TeV γ -rays and the X-rays are assumed to be produced by the same electrons.

However, the rim could also be explained as the region with strongly enhanced magnetic field behind the shock. The rim width then reflects the length scale of damping the magnetic turbulence rather than cooling of TeV electrons [16] (see also the discussion in [17]). Relativistic electrons accelerated at the rim escape from zone 1 (the rim) into the zone 2 by diffusion and/or convection with the fluid. The theory of cosmic-ray transport is highly developed, and involves at least the spectrum and anisotropic character of the turbulence [e.g., 18, 19]. Nevertheless, reasonably accurate general estimates can be made. For Tycho the convective escape time $\tau_c = h/v'_\text{fl} \approx 40 \text{ yr}$, where $v'_\text{fl} \approx v_\text{sh}/4 \approx 500 d_{\text{kpc}} \text{ km s}^{-1}$ is the fluid speed in the forward shock frame. The diffusive escape time from zone 1 is $\tau_\text{dif} \approx h^2/(2\kappa)$ where $\kappa = \lambda_\text{sc} c/3$ is the diffusion coefficient. The mean scattering length λ_sc of relativistic particles is equal to the gyroradius r_gyr in the Bohm diffusion limit, which is attained if the ratio of the turbulent magnetic field fluctuations to the mean field is $\eta = |\delta B|/B \simeq 1$. A value $\eta < 1$ is probably more realistic in general. In this case $\lambda_\text{sc} \approx r_\text{gyr}/\eta^2$ (e.g., [15]).

The diffusive escape time of electrons with Lorenz factor γ from the rim can be estimated as $\tau_\text{dif} \approx 1.1 \times 10^4 \eta^2 B_\mu \text{G} d_{\text{kpc}}^2 \gamma^{-1} \text{ yr}$. Comparing this with the synchrotron cooling time $t_\text{syn} \approx 2.45 \times 10^{13} B_\mu^{-2} \gamma^{-1} \text{ yr}$, one finds that accelerated electrons (of any energy) could cool in the rim before escaping downstream only if $B \geq 1.31 \eta^{-2/3} \text{ mG}$. Even in the limit of $\eta = 1$ this field is high. For any smaller magnetic field, electron escape from the acceleration region before cooling cannot be prevented. We note that this very effect explains the detection of non-thermal X-rays not only from the rim but also from a wider region interior to the rim.

Weaker magnetic fields interior to the thin rim could be the result of dissipation of the magnetic turbulence in the thermal plasma downstream of the forward shock on timescales $\tau_c \text{ yr}$. Therefore the region of the shell interior to the rim forms zone 2. This zone extends at least down to the contact discontinuity at $r_\text{CD}/r_\text{sh} \approx 0.927$ [4], in which case the volume V_2 of zone 2 is larger by a factor ≈ 3.3 than the zone 1 volume $V_1 \approx 0.05 V_\text{SNR}$. In a more elaborate model, the region between the contact discontinuity and the reverse shock at $\theta \approx 183''$ would be interpreted as another zone with a different set of source parameters. However, because the prime goal of this paper is to establish the need for multi-zone modeling, which is appropriate for spatially inhomogeneous sources and can significantly relax the constraints on the synchrotron and Compton fluxes compared to the single-zone model, here

we limit our calculations within the framework of two zones only. This assumes that zone 2 includes most of the shell between the thin X-ray rim (the zone 1) and the reverse shock. This is qualitatively justified as the contact discontinuity is apparently porous, with both thermal gas and relativistic particles penetrating through the contact discontinuity further down, e.g., through Rayleigh-Taylor instabilities as evident from detection of thermal X-ray filaments [e.g., 3, 7]. The implied volume filling factors of the two zones in the remnant are $\zeta_1 = V_1/V_\text{SNR} \approx 0.05$ and $\zeta_2 = V_2/V_\text{SNR} \lesssim 0.5$. These values can accommodate both interpretations of the X-ray stripes in Tycho [20] as part of either zone 1 (as further inhomogeneities in the rim [20]) or zone 2 (inhomogeneities in the shell).

The system of coupled equations describing the energy distribution functions $N_1(E, t)$ and $N_2(E, t)$ of electrons (or protons) in a two-zone model was derived in [12]:

$$\frac{\partial N_1}{\partial t} = \frac{\partial(P_1 N_1)}{\partial E} - \frac{N_1}{\tau_c} - \left(\frac{N_1}{V_1} - \frac{N_2}{V_2} \right) \frac{V_1}{\tau_\text{dif}} + Q_1 \quad (1)$$

$$\frac{\partial N_2}{\partial t} = \frac{\partial(P_2 N_2)}{\partial E} + \frac{N_1}{\tau_c} + \left(\frac{N_1}{V_1} - \frac{N_2}{V_2} \right) \frac{V_1}{\tau_\text{dif}} + Q_2 \quad (2)$$

Here $P_1 \equiv P_1(E, t)$ and $P_2 \equiv P_2(E, t)$ represent the energy-loss rates ($-dE/dt$) of particles with energy E in zones 1 and 2 respectively. The second term in the right side describes convective escape of electrons from zone 1 into zone 2, and the 3^{rd} term describes the diffusive escape of electrons from the zone 1 into zone 2 and vice versa proportional to the *difference* of the spatial densities (*the gradient*) of their energy distributions in the transition region between the zones. This leads to vanishing of the diffusive exchange of particles between the zones at very high energies when the energy densities in the two zones become equal. The timescale $\tau_\text{dif}(E)$ depends primarily on the diffusion rate in zone 1 because diffusion there is much slower (see [12] for details). $Q_1 \equiv Q_1(E, t)$ and $Q_2 \equiv Q_2(E, t)$ are the acceleration rates of particles in zones 1 and 2, respectively.

The integral form of the solution for this type of equation sets can be used to find a self-consistent solution for the system using the numerical method of iterations [13], neglecting the diffusive influx of particles from zone 2 to zone 1 in the first iteration. Calculations show that $\lesssim 50$ iterations result in a stable (converged) solution for $N_1(E, t)$ and $N_2(E, t)$.

III. MODEL PARAMETERS AND RADIATION FLUXES FOR TYCHO SNR

Fluxes of γ -rays produced by relativistic electron bremsstrahlung or by hadronic pp -interactions are proportional to the target gas density n_p (in terms of hydrogen atoms) in the source. The gas density n_1 in zone 1 (the rim) is proportional to the ambient gas density n_0 upstream of the forward shock, and is about $n_1 \approx 4 n_0$

for a strong shock. Modeling of the X-ray emission lines suggests [7] the best fit ambient gas density $\rho_0 = m_p n_0 \simeq 2 \times 10^{-24} \text{ g cm}^{-3}$, or $n_0 \approx 1.2 \text{ cm}^{-3}$ (see also [21]). Smaller values, in the range $n_0 \simeq (0.3 - 1) \text{ cm}^{-3}$ for distances $d \simeq (3 - 2.35) \text{ kpc}$, respectively, have been inferred from hydrodynamic modeling of the X-ray emission of forward-shocked material [22].

The mean gas density n_2 in zone 2 (the shell) can be derived from the estimate of the total gas mass accumulated in zone 2, $M_2 \approx m_p n_2 \zeta_2 V_{\text{SNR}}$, where ζ_2 is the volume filling factor. Note that in general this mass is contributed not only from n_0 , but also from the mass of the pre-supernova wind swept up by the forward shock, and the mass M_0 of the SN ejecta. To calculate M_2 we note that the measured speed of the forward shock is significantly smaller than the initial $v_0 \approx 10^4 (E_{\text{SN},51})^{1/2} M_{0,\odot}^{-1/2} \text{ km s}^{-1}$. For a typical Type Ia SN ejecta with ejecta mass $M_{0,\odot} = (M_0/M_\odot) \approx 1$ and kinetic energy $E_{\text{SN},51} = E_{\text{SN}}/10^{51} \text{ erg} \approx 1$ this implies up to several Solar masses residing in the shell of Tycho.

Indeed, most of the initial explosion energy should still be in kinetic form as both the total irradiated energy and the energy accumulated in accelerated particles are much smaller than E_{SN} . The total energy of the thermal electrons with temperature $kT_e \sim 1 \text{ keV}$ deduced from X-ray observations [3, 4, 7] is only $E_{T,e} = (3kT_e/2)M_2/m_p \approx 2.5 \times 10^{48} (M_2/M_\odot) \text{ erg}$. To contribute substantially to the total energy budget in the shell, thermal proton plasma should have a temperature of order $T_p \gtrsim 10^9 \text{ K}$. This is unlikely given fast heating of the electrons through Coulomb interactions with protons in such two-temperature plasma. Thus, the kinetic energy of the fluid moving with $v_f \simeq 3v_{\text{sh}}/4$ behind the forward shock in the shell should be still close to the initial energy, $E_{\text{kin}} = M_2 v_f^2/2 \simeq 10^{51} E_{51} \text{ erg}$. For $v_{\text{sh}} \approx 4600 (d/2.3) \text{ kpc}$ [5] the implied gas density in zone 2

$$n_2 \approx 1.05 \zeta_2^{-1} (d/3 \text{ kpc})^{-5} E_{51} \text{ cm}^{-3}. \quad (3)$$

For $\zeta_2 = 0.5$ this leads to n_2 in the range from 5 cm^{-3} for $d = 2.5 \text{ kpc}$ to $\approx 0.9 \text{ cm}^{-3}$ for $d = 3.5 \text{ kpc}$. In calculations here we use $n_2 = 3 \text{ cm}^{-3}$ corresponding to $d \approx 2.8 \text{ kpc}$.

For the Compton radiation we take into account not only the CMB target photons, but also the FIR photons produced by thermal dust in the NE and NW parts of Tycho [6]. This component can contribute up to 30% to the total Compton flux at TeV energies.

The particle injection rate Q_1 is in general time-dependent, reaching the maximum at the transition time to Sedov phase, and gradually declining afterwards. However, taking into account that Tycho is still in its early Sedov phase, we assume a stationary injection rate $Q_1(E, t) \propto E^{-\alpha} e^{-E/E_{\text{cut}}}$ with $\alpha = 2.3$ and $E_{\text{cut}} = 36 \text{ TeV}$. Given that the reverse shock in Tycho is not a bright non-thermal X-ray source, injection of electrons in zone 2 at the reverse shock is presumably much smaller than at the forward shock. To keep the model simple, we neglect electron acceleration in zone 2, i.e. $Q_2 = 0$.

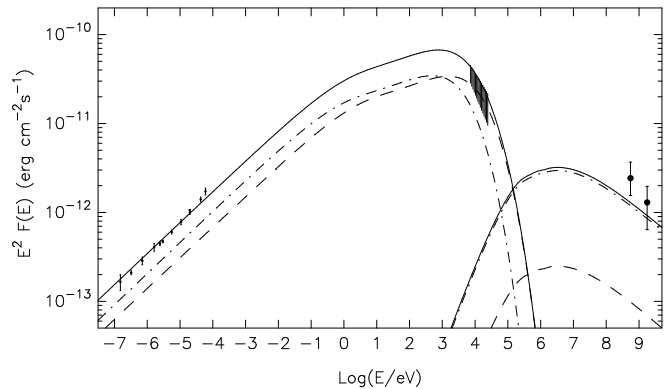


FIG. 1: The synchrotron fluxes from radio through X-rays in the two-zone model. Dashed and dot-dashed lines show the fluxes from zone 1 and zone 2, respectively, and the total flux is shown by the solid line. Calculations assume density $n_2 \approx 3 \text{ cm}^{-3}$ at $d_{\text{kpc}} = 2.8$, and $n_1 \approx n_2$. Other model parameters are $B_1 = 100 \mu\text{G}$ and $B_2 = 32 \mu\text{G}$, $\eta = 0.3$, $\alpha = 2.3$ and $E_{\text{cut}} = 36 \text{ TeV}$. Also shown are $\lesssim \text{GeV}$ bremsstrahlung fluxes produced by relativistic electrons in zones 1 and 2.

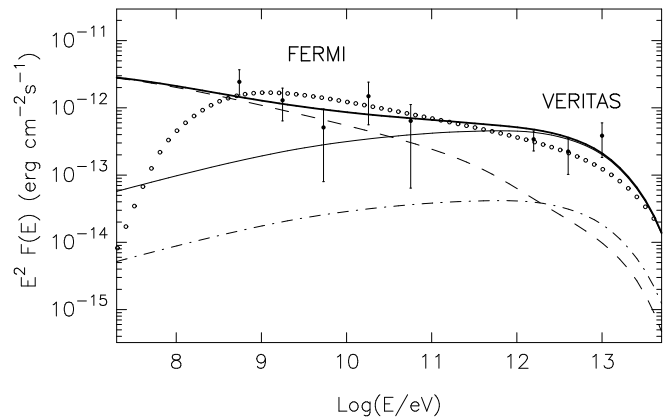


FIG. 2: The γ -ray fluxes produced in the two-zone model. The heavy solid line shows the total flux of leptonic origin. The total bremsstrahlung and Compton radiation fluxes are shown by dashed and solid (thin) lines, respectively. Both are predominantly produced in zone 2. For comparison, the Compton flux contribution from zone 1 is also shown (dot-dashed line). The full open dots show a possible fit to data by a hadronic model (see text).

Figure 1 shows the synchrotron fluxes from radio through X-rays calculated assuming $B_1 = 100 \mu\text{G}$ and $B_2 = 32 \mu\text{G}$ in zone 1 and zone 2, respectively. In the radio to sub-mm wavelengths the total flux is contributed mostly by zone 2, while in non-thermal X-rays zone 1 contributes more than zone 2. This picture is in qualitative agreement with observations that the narrow rim is much brighter in X-rays than in radio.

Figure 2 shows the γ -ray fluxes. The total flux of leptonic origin is dominated by bremsstrahlung up to $\sim 100 \text{ GeV}$, most of which is produced in zone 2 where most of electrons accelerated in zone 1 eventually reside.

The assumed mean gas density $n_2 \approx 3 \text{ cm}^{-3}$ in zone 2, at $d = 2.8 \text{ kpc}$, implies about $3 M_\odot$ of gas accumulated in the shell of Tycho. The gas density n_1 in zone 1 doesn't have any significant impact on the calculated fluxes. A density n_1 in the rim about the same as the average n_2 in the shell would imply an ambient gas density $n_0 \approx n_1/4 = 0.75 \text{ cm}^{-3}$. Even lower gas densities n_0 cannot, however, be excluded taking into account that the mass currently accumulated in the shell may have a composition dominated not by the swept up ambient gas but by the presupernova wind.

The total energy of the electrons in zones 1 and 2 are $E_{e,1} = 4.4 \times 10^{47} \text{ erg}$ and $E_{e,2} = 4.3 \times 10^{48} \text{ erg}$, respectively. The thin solid line shows the total Compton flux. Because the target photon field (CMBR + FIR) penetrates easily through the entire source and thus is same in both zones, the Compton contribution from zone 1 is insignificant.

The detected γ -ray fluxes can also be explained by relativistic protons. Full open dots in Figure 2 show the flux from π^0 decay γ -rays produced by protons with the power-law index $\alpha_p = 2.3$ and the total energy $E_p = 3 \times 10^{49} \text{ erg}$. We emphasize that the essential difference between the hadronic and leptonic fluxes occurs only at energies below $\approx 500 \text{ MeV}$. Therefore only by detecting the characteristic π^0 decay cutoff in the energy spectrum of γ -rays at $E \simeq (100 - 300) \text{ MeV}$ will it be possible to claim that cosmic ray hadrons are the origin of the γ -rays from Tycho.

IV. SUMMARY AND DISCUSSION

Clear identification of the π^0 decay bump peaking at $E = m_{\pi^0}/2$ in a photon spectrum was proposed long ago as a promising way to establish acceleration sites of cosmic-ray protons and nuclei [23, 24]. The Large Area Telescope on *Fermi* provides a new database for tackling this question, and the Type Ia SNR Tycho presents one of the best opportunities to search for signatures of hadronic production.

Any realistic treatment of the acceleration and radiation must consider at least two zones of different magnetic field strength. Electrons in the thin acceleration zone behind the shock where the field is enhanced are

bright in synchrotron X-rays. Electrons in the region with the weaker field (zone 2) occupying the bulk of the shell volume will have dim synchrotron emission, and can be essentially missed in single-zone analyses. This zone can, however, provide most of the Compton and bremsstrahlung flux. This effect significantly weakens limitations inferred from a single-zone analysis of the observed synchrotron X-ray and GeV-TeV γ -ray fluxes. With a more realistic two-zone model, we find that a good fit to the Fermi and VERITAS data from the Tycho SNR can be made by a purely leptonic model, with bremsstrahlung emission making, primarily, the GeV γ rays, and TeV photons coming mainly from Compton-scattered soft radiation fields. No hadrons are required in this model. The underlying densities and volume filling factors of the two zones are not uniquely parameterized, our solution represents only one of a range of possibilities.

Figure 2 shows that hadronic models can fit the data just as well as a leptonic model. The two models are quite different only at low energies, with the hadronic model exhibiting the π^0 -decay feature, shifted up to a few hundred MeV in a νF_ν representation (e.g. [25]). The absence of this low energy feature would rule out a hadronic origin, while its detection would support an origin from cosmic-ray protons and ions.

Establishing the flux of Tycho at low energies with the *Fermi*-LAT is difficult because of the reduction in the effective area and the larger point spread function below 1 GeV [26]. Moreover, background modeling of the diffuse γ -ray emission from the Galaxy disk has to be carefully treated. Progress in low-energy analysis and longer exposure times will help improve the quality of the *Fermi*-LAT spectrum of Tycho. The kinematic π^0 flux reduction is, however, a generic feature of cosmic-ray hadron origin from the GeV cosmic rays that carry most of the energy. Identification of this feature in Tycho or other SNRs will finally provide experimental confirmation of the SNR origin of the Galactic cosmic rays.

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